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A Digital Processor for Detecting Small
Signals in Periodic Interference

by M. C. Bartlett

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A digital processor for FM/cw IF-correlator ranging systems which detect small IF signals in periodic interference is described. The processor is based on a high-speed low-resolution (6 to 8 bits) A/D converter synchronized to the ranging system. The study shows that signals below and above the quantization level can be reliably and linearly processed. The processor is shown to be insensitive to variations in interference waveform amplitude and shape. A digital correlator/comb-filter is used to eliminate responses from

periodic interference.

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FIGURES

1. INTRODUCTION

In recent years, the Electronic Communications Laboratory has been involved in the development of short-range homodyne FM/cw radar systems.[1] These systems measure range by processing the IF signal, which results from mixing the transmitted and received signals. Some small systems employ a common transmit/receive antenna and obtain the IF signal by detecting the envelope of the composite RF antenna voltage. Ideally, the transmitter amplitude does not vary with FM and the detector output is the desired IF signal along with a dc voltage corresponding to the transmitted signal level. If, however, the transmitter amplitude varies with FM, large undesirable components corresponding to the modulation frequencies are generated and more elaborate signal processing techniques are required. The interfering components introduced by frequency modulating the transmitter are generally indistinguishable from large short-range clutter targets; and consequently, signal processing techniques developed for FM/cw radars in a clutter environment are generally applicable.

A variety of useful coherent detector and comb-filter techniques have been developed to measure the amplitude of an IF signal in a high-level periodic interference (Selected Bibliography). One useful technique employs a multiplying digital to analog converter (MDA) to correlate a digital IF reference corresponding to a particular range with the RF detector output containing the target IF signal and the interference.[2] The correlator output due to moving targets is separated from the output from periodic interference by a doppler filter. The amplitude of the doppler signal provides an unnormalized measure of target range. The MDA exhibits good dynamic range and has proved successful in processing signals 70 dB below the interference.

In view of the continuing rapid development of digital processing techniques and devices, a study was initiated to determine the feasibility of digital FM/cw IF-correlator ranging systems. Techniques for digitizing the RF detector output, correlating with a stored reference, and filtering to produce a digital doppler signal are discussed in this report. Digital doppler processing techniques will be examined in future studies.

Several significant results were obtained from this study. First, the study established that IF signals below the analog to digital (A/D) converter quantizing amplitude can be successfully processed. This is an important result because of the rapid advances in high-speed, low-resolution (6 to 8 bits) A/D converters. Second, the study demonstrated that the digitized interference is predominantly periodic and can be removed by the coherent detector/doppler-

[1] William K. Saunders, CW and FM Radar, Chapter 16 in Radar Handbook, Merrill I. Skolnik, Editor, McGraw-Hill (1970).

[2] M. C. Bartlett and R. C. Johnson, Hybrid Modulation/Demodulation Techniques for Implementing IF Correlator FM Ranging Systems, University of Florida, under contract to Harry Diamond Laboratories, HDL-CR-77-045-3 (August 1977).

filter techniques previously employed. This result means that the signal is
about 10 dB more detectable than would be the case for random digitizing errors.
Third, a technique for synchronization of the A/D converter, correlator, and
digital averager is described which results in low noise and sin x/x filtering
of the correlator output with nulls at harmonics of the modulation frequency.
A simple digital high-pass filter removes the mean correlator output resulting
in a digital doppler signal with positive S/N ratio. Further, the digital
processing technique was found to be inherently insensitive to variations in
interference with a dynamic range nearly equivalent to hybrid MDA techniques.
This study shows that digital FM/cw IF-correlator radars are practical and
offer an attractive option for the system designer.

2. DIGITAL FM/CW IF-CORRELATOR TEST SYSTEM

Figure 1 illustrates the test system for this study. A modulo-256
digital modulation m(i) frequency modulates the FM/cw oscillator. The de-
tector output is digitized by an 8-bit A/D which is synchronized to the
system clock. The A/D converter converts a normalized analog signal
$[-1 \leq x \leq 1]$ to a normalized digital signal $[-1 \leq y \leq 127/128]$. The digitized
signal is multiplied by the stored IF reference R(i). The product is scaled
down by 32 and accumulated over the 256-sample period by a clocked register
and full adder. At the end of each modulation cycle, the accumulator register
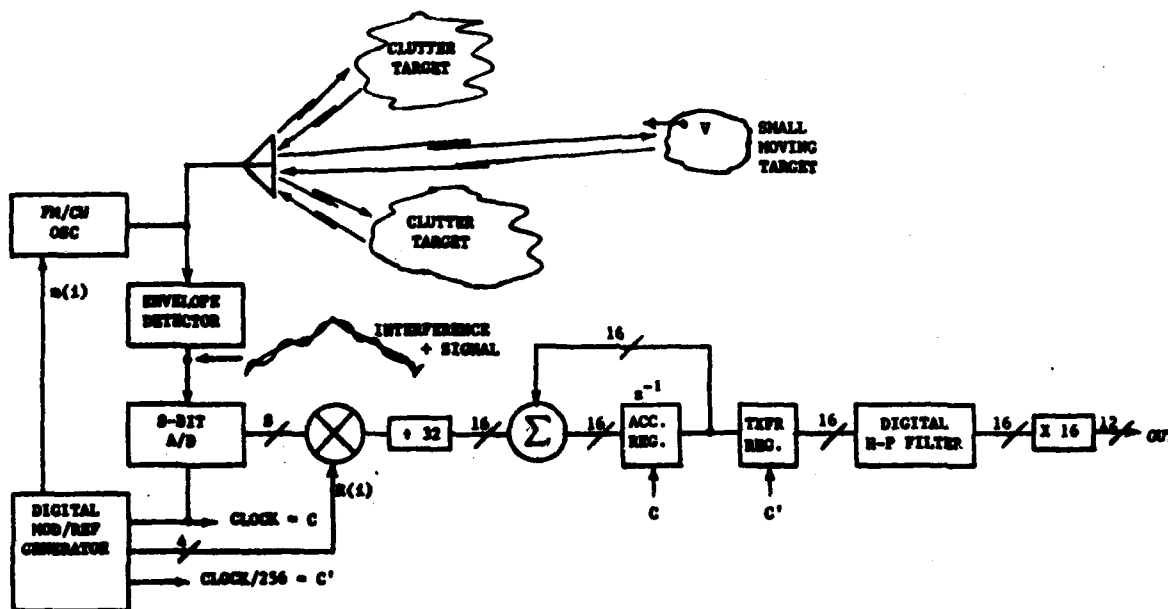output is set into a transfer register (TR) and the accumulator is reset to
zero.

Figure 1. Digital-processor test system.

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The transfer register samples and holds the correlator output each modulation period. This operation gives a sin x/x filter response with nulls at multiples of the modulation frequency, thus eliminating the need for further low-pass filtering. The sin x/x filter does not exhibit a null at zero, and the TR output will have a mean value produced by correlating the reference with the periodic interference over the modulation period. A digital high-pass filter removes the mean correlator output. The filter output is scaled up by 16. The result is a signal which has been comb filtered to remove fixed interference responses at zero frequency and multiples of the modulation frequency.

An IF signal from a moving target produces a doppler signal which is passed by the digital high-pass filter. Ideally, the A/D converter response to periodic interference is periodic and is removed by the comb-filter technique. In practice, the digitized interference will have some variability due to errors or noise, and the digital output will exhibit a residual noise level. Test results have shown the residual noise to be 8 to 10 dB below that expected for random 1-bit digitizing errors. The response is linear for signals below and above the quantizing amplitude.

3. A/D CONVERTER RESPONSE FOR SMALL SIGNALS IN PERIODIC INTERFERENCE

A clocked A/D converter can be modeled as an amplitude quantizer followed by a time sampler. The A/D response to small signals in periodic interference, described in the following sections, is discussed more fully in appendix A.

3.1 Amplitude Quantizer Response

The effects of a signal on a normalized amplitude quantizer driven by periodic interference is illustrated by the transfer function sketch of figure 2.

The periodic input will cause the quantizer to switch at fixed points resulting in an output which is a non-linear function of the interference. Adding a signal perturbs or modulates the quantizer switching point as shown by the dotted lines. The quantizer output due to periodic interference and a signal with amplitude δ can be modeled as the sum of the output due to interference alone added to pulses with amplitude $\pm q$ (q = quantizing amplitude) and width $\delta/(q/\Delta T)$, where $q/\Delta T$ is the slope of the interference waveform. Assuming a uniform density about each switch point, the computed average shows the quantizer output to be shifted by exactly δ. Small signals are seen to be pulse-width modulated with samples taken at the quantizer switch points.

For small signals, the process is dependent on the periodic interference to provide enough quantizing switch points to adequately sample the signal. The process is not dependent on linear interference. For non-linear interference, the quantizer samples will not be uniformly spaced in time. However, the probability density of the quantizer input is inverse to the slope of the interfering signal; and consequently, the signal pulses will be shortened or lengthened as required to give the correct signal area. The process is

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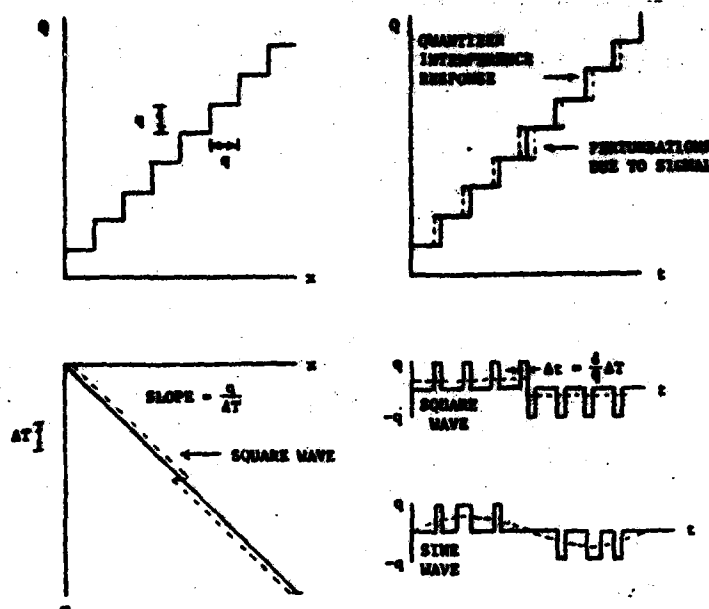therefore not sensitive to the amplitude and shape of the interference
waveform.

Figure 2. Amplitude quantizer with linear interference
and representative signals.

For an interference waveform with slope S, the sampling frequency due
to crossing quantizer switch points is

$$f_q = \frac{S}{q} \tag{1}$$

3.2 Time-Sampled Quantizer

The quantizer output is time sampled by the system clock to complete
the digitizing process. For interference waveforms with varying amplitude
and shapes, the position of the time sample with respect to a given quantizer
switch point is random and is uniformly distributed. From this it follows
that the average perturbance for a sampled quantizer is the same as for an
unsampled quantizer. However, the fact that the average (averaged over
different interference waveforms) is correct does not insure that the signal
has been properly time-sampled for a particular interference waveform.

If the time-sampling frequency is f_s, the average _signal_ time-sampling
frequency f_s^1 is given by

$$f_s^1 = f_s \left(\frac{s}{q}\right); \quad 0 \leq s \leq q .$$

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The number of samples which fall in the area perturbed by the signal is f_s^1. For small signals ($\delta < q$), the effective sampling frequency is bounded by the number of quantizer switch points. Denoting the effective sampling frequency by f_e, the relationship can be expressed by

$$f_e \leq \text{smaller of } [f_q, f_s^1] \ . \tag{3}$$

Since signal detectability is limited by random digitizing errors or an equivalent self-noise, the gains from increasing the time-sampling frequency is limited. For the system tested, f_s was approximately equal to f_q.

4. CALCULATED RESPONSES

If the input contains random fluctuations which are independent from sample to sample with variance σ_n^2, the output expected is

$$\sigma_0 = 8\sigma_n\sigma_R \ , \tag{4}$$

where σ_R^2 is the variance of the stored reference.

For a 1-bit random error, the expected output is

$$\sigma_0 = 8\left(\frac{q}{2}\right)\sigma_R \ , \tag{5}$$

where q is the quantizing amplitude.

The response expected from an IF signal is

$$\sigma_0 = \frac{128}{\sqrt{2}} \sigma_S\sigma_R\rho_{SR} \ , \tag{6}$$

where ρ_{SR} is the correlation between the signal and the reference.

Assuming $\rho_{SR} = 1$, a comparison of (6) with (4) shows a signal gain of 21 dB as compared to a random, independent noise input. Since the measured self-noise was 8 to 10 dB below that for random 1-bit errors, signal detectability is approximately 30 dB below the quantizing amplitude. For an 8-bit A/D converter, 1-bit quantizer noise is 43 dB below full-scale linear interference. The result is that signals more than 70 dB below the interference are detectable.

The reduction in random noise errors as indicated by (4) is due to averaging 256 independent samples. If the samples are not independent, the residual noise level will increase. As noted previously, the digitizer samples the signal or noise, and an adequate number of samples is required

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to recover the signal. It is desirable to have a large number of quantizer steps to allow as many independent noise samples as possible.

Equations (4), (5), and (6) are normalized. Inputs are normalized by dividing by the full-scale value of the system input. Normalized outputs are scaled for testing experimental systems by multiplying by full-scale values (e.g., 2048 for a 12-bit integer output or 10 V for a ±10-V D/A converter output).

5. TEST RESULTS

The first test was conducted to verify the gain and linearity of the digitizer as the signal was varied through the quantizing amplitude. The sensitivity of the signal gain was tested by varying the shape and amplitude of the periodic interference for a fixed input signal. Figure 3 illustrates the test configuration. The A/D and D/A were truncated to 5 bits to give an input quantizing level of 64 mV. The system clock operated synchronously at 4096 kHz to eliminate time quantiziation effects. An almost full-scale 16-kHz triangular interference was injected so that there were approximately 60-quantizer steps per modulation cycle to sample the signal. Low-pass filtering eliminates the quantized interference waveform allowing the output signal to be monitored.
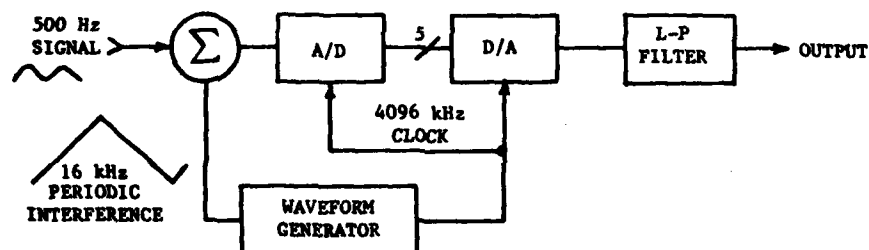

Figure 3. Digitizer test configuration.

The signal was varied from 5- to 160-mV rms at the A/D input. The observed output varied linearly with the input signal with unity gain. Variations of interference amplitude and shape caused no observable effects. Overdriving the A/D with the interference simply gates out that portion of the signal.

The following tests were conducted with the digital processor illustrated in figure 1. The correlation/comb-filter response to random digitizing errors was tested by injecting 1-bit random errors on the A/D output. The output variance was calculated from equation (5) and verified by measurements for the following cases: (1) a positive full-scale reference ($\sigma_R = 7/8$), (2) a cosine reference with two cycles over the modulation cycle ($\sigma_R = 0.707$) and, (3) a weighted cosine reference with 8 cycles over the

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modulation cycle (σ_R = 0.545). A 1-bit random variation corresponds to $\sigma_n = \frac{q}{2}$ = 1/256 for an 8-bit A/D.

Full-scale triangular interference was injected and the residual noise tested for the three references previously tested. The residual noise was reduced by 8 to 10 dB, illustrating that the least significant bit of the A/D is not random but is controlled primarily by the periodic interference. The residual noise is dependent on circuit construction, and further reductions may be possible. IF signals were tested and the output measured to verify (6).

The number of bits of the quantizers varied from 8 down to 4, and the observed residual noise varied from 9×10^{-3} to 30×10^{-3}. The variation is approximately as expected from reducing the number of independent noise samples. This test indicates that many low-height FM/cw IF-correlator ranging systems can be implemented with 6 to 8-bit A/D converters.

Figure 4 illustrates the comb-filter response with nulls at zero frequency and multiples of the modulation frequency f_m. Residual noise raises the measured sin x/x nulls above zero and obscures the fact that the comb-filter null response is zero for periodic interference.
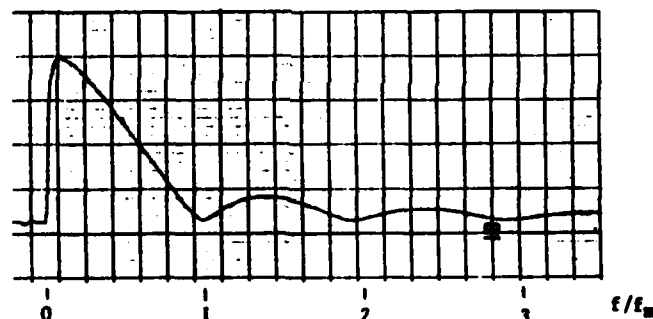

Figure 4. Comb-filter response.

6. CONCLUSIONS

This study investigated the feasibility of digital processing for FM/cw IF-correlator ranging systems which detect small IF signals in periodic interference. This investigation produced several major conclusions. First, the digitizer (A/D) noise can be minimized by synchronizing a low-resolution (6 to 8 bits) A/D converter to the ranging system. The digitizer output due to periodic interference is then primarily periodic and can be removed by the coherent detector/comb-filter techniques previously developed. Second, the perturbance of the quantizer switch points by a small signal gives a reliable and linear method of detecting signals below and above the quantization level. This process is insensitive to the amplitude or shape of the interference waveform, provided enough quantizer switch points are crossed to adequately sample the signal. Third, averaging the correlator output over the modulation period gives a sin x/x comb-filter response with nulls at

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multiples of the modulation frequency so that further low-pass filtering is not required. Fourth, the residual noise due to quantization errors is about 10 dB below that for 1-bit random errors, resulting in signals detectability over 70 dB below full-scale interference for an 8-bit A/D converter. This study established that digital processors are feasible and practical for FM/cw IF-correlator ranging systems and offer an attractive option for the system designer.

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Acknowledgements

APPENDIX A.—A/D CONVERTER RESPONSE FOR SMALL
SIGNALS IN PERIODIC INTERFERENCE

Section 3 described the output of an A/D converter driven by the sum
of a signal and periodic interference. The sensitivity of this process to
variations in interference waveform amplitude and shape is of particular
importance if the process is to have practical application. The linearity
of the quantizer output for signals below and above the quantization level
is also of interest. This appendix examines these effects in more detail.

A-1. AMPLITUDE QUANTIZER RESPONSE

The quantizer output due to a signal is analyzed by the following pro-
cedure. First, the periodic interference (x) is partioned uniformly into
q-wide sections centered on the quantizer switch points x_k. To give a one-to-
one correspondence between the interference time waveform and the partitioned
section, x is further partitioned into monotonic sections (j). The contri-
bution of each section can be analyzed using the joint probability density
$p(x, j)$. Figure A-1 illustrates a periodic interference waveform with 3
monotonic sections.

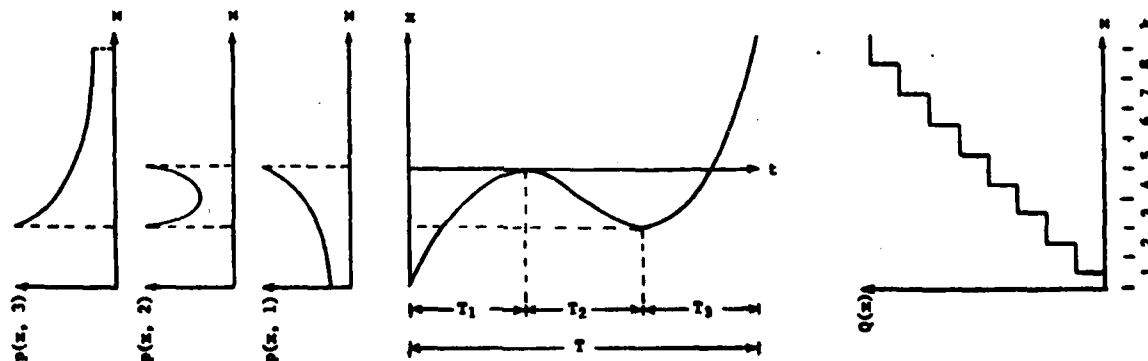Figure A-1. Monotonic interference sections.

Second, a signal with amplitude δ is modeled as a perturbance of the
quantizer function $Q(x)$ to give $Q(x + \delta)$. The effect of a signal on section
(j, k) is found by statistically averaging the perturbed and unperturbed
quantizer function using $p(x, j)$. Figure A-2 gives an expanded view of A-1
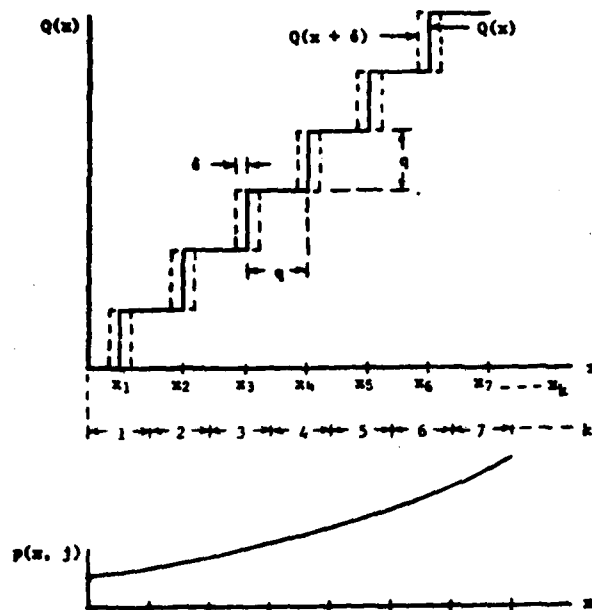for a particular monotonic section.

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Figure A-2. Quantizer analysis for monotonic section.

The contribution of a particular section (j, k) due to a signal is the difference between the quantizer output with a signal present and the quantizer output with no signal. This difference is computed by

$$C(\delta, j, k) = \int_{x_k-q/2}^{x_k+q/2} [Q(x + \delta) - Q(x)]p(x, j)dx . \qquad (A-1)$$

For $\delta \leq q/2$,

$$C(\delta, j, k) = q \int_{x_k-\delta}^{x_k} p(x, j)dx . \qquad (A-2)$$

By identifying the time interval spent in the (j, k) quantizer section as $\Delta T(j, k)$ and assuming the slope is constant over the quantizer interval, the probability density for the interval can be written as

$$p_k(x, j) = \frac{1}{q} \cdot \frac{\Delta T(j, k)}{T} . \qquad (A-3)$$

Equation (A2) can then be evaluated as

$$C(\delta, j, k) = \delta \frac{\Delta T(j, k)}{T} ; \quad \delta \leq \frac{q}{2} . \qquad (A-4)$$

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Equation (A-4) shows that a signal causes a pulse of amplitude ±q with width $(\delta/q)\Delta T(j, k)$ so the contribution over the interval is the signal amplitude and that the process is linear. Processes which average parameters which are invariant in the interval will not distinguish between signals with amplitude-width $(\delta, \Delta T)$ and signals with amplitude-width $(q, \Delta T\frac{\delta}{q})$. However, the fact that the signal is sampled by the quantizer with a variable width aperture should be noted as this will affect some processes.

The preceding analysis also clarifies another important characteristic of this process. Since small signals are sampled by the interference-crossing quantizer switch points, the sampling rate is directly proportional to the slope of the interference waveform. However, equations A-2 and A-4 show that the contribution from a given switch point varies inversely with the slope of the interference waveform. These effects are compensating with the result that the process is not sensitive to the amplitude or shape of the interference waveform as long as adequate samples are taken. In effect, the signal can be represented by a series of narrow pulses or by a fewer number of wider pulses.

Interestingly, a quantizer interval with a slope which is not representative will produce a contribution which is not correctly weighted. The effect of non-representative samples will be diminished as the number of quantizer levels is increased; however, localized spots with low slopes can be expected to contribute to quantizer noise.

Analyzing the quantizer output as outlined previously for $\delta < q/2$ shows the process to be linear for signals below and above the quantizer level. The analysis is aided by defining $y = x - x_k$ and a perturbance function $F(\delta, y) = Q(x - x_k + \delta) - Q(x - x_k)$ which is averaged over a section using equation A-1. Figure A-3 sketches $F(\delta, y)$ for positive δ. The arrow coming from a shaded area shows the part of the shaded area which is increasing as δ is increased. For negative δ, $F(\delta, y)$ is mirror image with respect to both coordinates; that is, $F(-\delta, y) = -F(\delta, -y)$. If the probability density is uniform over the interval, the output is determined by the area under $F(\delta, y)$ rather than its exact structure, and the process is linear.
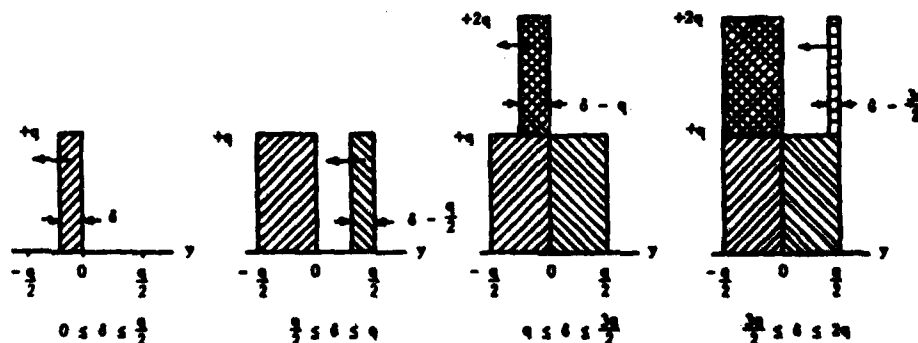

Figure A-3. Perturbance function $F(\delta, y)$ for positive δ.

Figure A-4 gives a three-dimensional picture of the perturbance function. $F(\delta_0, y)$ is the projection of a line, $\delta = \delta_0$, on the surface of the figure. For negative δ, the figure is mirror image with respect to both coordinates.
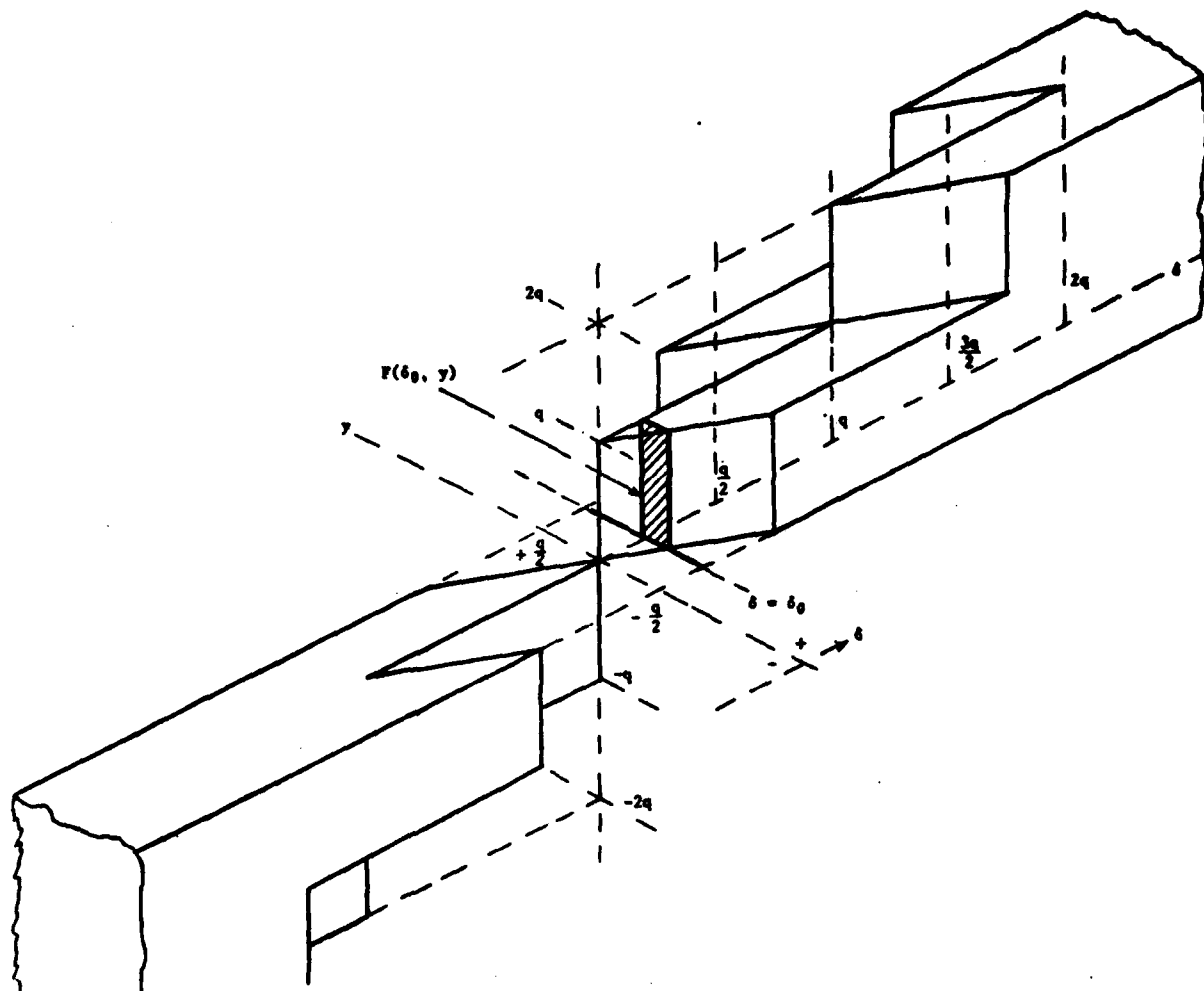

Figure A-4. Three-dimensional perturbance function.

A-2. TIME-SAMPLED QUANTIZER

For interference waveforms with arbitrary amplitudes and shapes, the position of the sample will be uniformly distributed with respect to the time of the crossing of a quantizer switch point. If the slope of the inter-ference waveform is constant over a given quantizer interval, the samples will also be uniformly distributed over the interval $\{q/2 \leq x - x_k \leq q/2\}$. For this case, the quantizer sample mean will be equal to the quantizer mean, and the effect of a signal will be the same as described in the previous section.

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As noted in section 3.2, this result does not insure that signals below the quantizing amplitude have been adequately time sampled. The effective sampling frequency for small signals is limited by both amplitude quantization and time sampling (equation 3). Equation 2 implies that f_s can be increased as needed to detect very small signals. In practice, this process is limited by the fact that random digitizing errors or equivalent self-noise limits signal detectability and further increases in f_s are ineffective. An alternative view is that residual noise broadens the quantizer switching characteristic so that small signals can be detected with fewer samples. The high-speed low-resolution A/D converters now available are well suited to IF-correlator FM-ranging system applications. In most cases, several samples can be summed before correlating with the IF reference. This step will be helpful in reducing the speed requirements of the multiplier-accumulator hardware.

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